

COMPARATIVE SPEEDS AND VARIABILITY OF MOTION OF THE FINGERS OF MAN

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Among the problems of space biology, one of the most vitally necessary is the problem of evaluating the effector activity of man. On the state of this activity depends the solution of the problem of the relative degree to which an automat or a human being will participate in spaceship control. Of extraordinary importance are the development and substantiation of tests which will permit operative and reliable evaluation, within a short period of time, of human control qualities, such as control of his speed of motion in precise execution of some program of actions.

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However, there are still many unexplained aspects. The first relates to the maximum speed developed by a human being in striking keys with the fingers. The figures cited by various authors fluctuate from 5 - 6 motions per second [5] to 10-11 [2].

The second aspect, which was first examined in detail by Miles, has to do with the possibility that there exists a certain range of fixed speeds of human motions. Miles' data speak in favor of the existence of distinct classes of rates of motion, but must be further clarified, since they contain many cases of overlap.

The third unclarified aspect deals with correlation of the rate of motion between individual fingers of the right and left hands. Goodenough and Tinker [4] emphasize the good correlation in the speed of motion of different fingers of one hand and the poor correlation of fingers of the other hand. Jackson, however, cites contradictory data and says that the speed of motion of the ring and little fingers is slower than that of the other fingers, while Lunderfold [6] cites data testifying that the bioelectric activity of the muscles while typing with the ring and little fingers is distinctly higher than that of the other fingers. Thus, the problem of correlation insofar as speed of motion is concerned remains open.

The aim of the present research reduced to the study of the temporal characteristics of the motion of each finger of the right and left hands, with the test subjects being allowed to freely choose their own speeds ("optimal," "fast" and "slow"). The motions in mind are striking, with the finger, one of the teletype keys intended for the given finger. Each finger struck a key about 100 times in succession at each of the above-mentioned speeds.

The total time spent for each action consisted of the time interval required for accomplishment of the task (the pressing time) and that required to lift the finger and lower it again (the length of the pause).

This kind of experiment permitted us to examine the following aspects of the problem.

1. What are the frequency characteristics of the motion of various fingers of a human being at each of speeds set by himself and what are the relations between the chosen speeds of the different test subjects.

2. How do these characteristics vary and to what extent does the variability depend on the fingers, the speed, and the personal peculiarities.

3. Do any distinct differences exist between the self-set speeds of motion ?

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4. Is the time interval required to carry out the motion organized or random?

METHOD

The motion carried out by the fingers was the striking of keys of an ST-2M teletype machine whose keyboard resembled in form, dimensions, and key arrangement the keyboard of a standard typewriter. Each key of the teletype machine has a contact sensor connected to a multichannel loop oscillograph of the N-102 type. The key notation (letters and numbers) was retained. To the working surface of the fingernail phalanx of each finger of the test subject we attached an electrode (a disk of thin foil, 1 cm in diameter) using BF-6 cement. Thin wires led from each disk and were fixed to the back of the fingers and wrist with leucoplaster; they were connected to the oscillograph by means of removable lasts, different ones for each wrist. Each finger had its own channel.

The records were made on the tape of a multichannel oscillograph at a tape speed of 25 mm/sec.

Contact between the electrode on the finger and the sensor on the key generated a rectangular pulse, the length of which corresponded to the length of contact with the key; the pulse separation corresponded to the finger lifting and lowering time (subsequently referred to as the pause).

The experiment was carried out with 3 test subjects. One of them (V. G.) had completed typewriting school and had experience in typing with all fingers. Two test subjects had typed periodically using the thumb, index and middle fingers of each hand.

The instructions informed the test subjects of the problem, which involved uniform depression of one key with the finger. They were required to work "as fast as possible," were allowed to choose the most convenient "optimal" working speed, and were asked to slowdown the "optimal" rate by a factor of 1.5. The instructions gave the order for change of fingers and working speeds, which were accomplished on a prearranged signal from the experimenter (thus it was not necessary to make an active count of the striking operations).

The same sequence of change of work speed was applied for all the fingers: first the "optimal," then the "fast," and finally the "slow." The experiment began with key-pressing operations by the thumb of the right hand at the "optimal" speed, followed by the same operation with the thumb of the left hand. After both thumbs had run through all the working speeds, they were succeeded by the index fingers in the same order of alternation of speeds and hands, etc.

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The parameters were measured by means of a photoamplifier provided with a measuring grid, accurate to within 10 msec. Measured were all parameters corresponding to length of the pressing actions and to the length of the pauses. The following were computed on the basis of the measurements made:

- 1) the duration of each motor cycle, equal to the sum of the pause length and the pressing time following the pause;
- 2) the mean time of the motor cycle, the mean square deviations and the coefficients of the variations, and the same for the components of the pauses and pressing actions;
- 3) evaluation of the distribution of intervals representative of the duration of the motor cycle.

RESULTS

Given in Tables 1, 2 and 3 are the mean arithmetic data on the lengths of the intervals for execution of motor cycles and their elements, individually for each test subject at various working speeds (fast, optimal and slow performance speeds). Table 1, which gives the corresponding values for test subject V.G. who differs from the others in that she is a professional typist, systematically trained, shows the following characteristics: /111

TABLE 1. Mean Values of the Duration of the Motor Cycle and Its Elements (in msec) for Various Pressing Speeds (Test Subject V.G.)

Finger	Speeds (mean data)											
	Fast				Optimal				Slow			
	No. of measurements	Length of cycle	Pressing time	Transfer time	No. of measurements	Length of cycle	Pressing time	Transfer time	No. of measurements	Length of cycle	Pressing time	Transfer time
Right hand												
1-thumb	—	—	—	—	—	—	—	—	—	—	—	—
2-index	113	220	120	95	123	310	100	215	101	615	375	235
3-middle	108	215	90	130	120	300	95	210	96	615	250	375
4-ring	99	230	100	125	109	380	95	290	107	610	175	435
5-little	69	240	100	140	91	425	110	315	94	610	170	440
Left hand												
1-thumb	—	—	—	—	—	—	—	—	—	—	—	—
2-index	104	245	140	105	124	310	115	200	106	630	330	300
3-middle	106	255	135	120	118	325	100	225	105	610	305	305
4-ring	101	250	165	90	105	405	130	275	102	620	305	315
5-little	88	250	180	75	93	465	180	285	108	595	315	275

- 1) the lengths of the motor-cycle intervals, at each speed, although they differ for different hands and fingers, do not exceed the limits distinguishing the various working speeds;

2) the smallest differences in length of motor cycles between pressing with different fingers and hands at the given speeds are observed for fast and slow work, amounting to 35-40 msec. At the same time, fluctuations in the length of motor cycles between individual fingers in the optimal case reach 165 msec;

3) in comparing the work speeds (at the given tempo) of the individual fingers, it can be seen that in the case of fast speed and, in part, of optimal speed, the fingers of the left hand lag those of the right hand, but at the slow pressing speed this is not observed;

4) fluctuations in key-pressing time for the individual fingers differ from the magnitude of the fluctuations and distribution with respect to the working rates of the entire motor cycle. Thus, at the slow speed, for fluctuations of 35 msec in the duration of the cycles, the magnitude of the fluctuations in pressing time was 200 msec, i. e., almost 6 times greater than fluctuations of the cycle. At the optimal working speed, the magnitude of the fluctuations in pressing time is 85 msec, i. e., one-half the magnitude of the fluctuations of the entire cycle. At the fast pressing speed, the ratio of fluctuation of the pressing time to that of the length of cycle is 2.2, i. e., midway as compared with the ratio of pressing time/length of the cycle at the optimal and slow pressing speeds.

Presented in Table 2 are data on the work of test subject E. F. Let us compare these data with those of the first test subject. From the data of Table 2 it is evident that:

TABLE 2. Mean Values of the Duration of the Motor Cycle and Its Elements (in msec) for Various Pressing Speeds (Test Subject E. F.)

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Finger	Speeds (mean data)											
	Fast				Optimal				Slow			
	No. of measurements	Length of cycle	Pressing time	Transfer time	No. of measurements	Length of cycle	Pressing time	Transfer time	No. of measurements	Length of cycle	Pressing time	Transfer time
Right hand												
1-thumb	120	225	90	165	154	405	155	255	136	575	200	389
2-index	138	255	95	160	91	530	165	365	124	620	185	435
3-middle	164	220	95	130	134	465	130	340	139	720	260	460
4-ring	142	230	115	110	135	475	180	295	117	645	205	435
5-little	128	270	115	140	132	530	215	315	113	695	220	470
Left hand												
1-thumb	74	265	80	185	149	450	150	305	119	625	170	455
2-index	127	245	95	155	109	590	165	420	72	620	170	455
3-middle	136	235	80	160	137	480	145	345	88	760	175	590
4-ring	134	235	100	140	134	500	205	300	115	715	195	520
5-little	122	260	95	165	115	535	225	310	115	735	215	525

1. the values of the motor-cycle intervals fluctuate at the same working speed, but are considerably closer to each other than the intervals characterizing the other speeds. There is only one case of overlap, when the index finger of the

left hand works somewhat slower at the optimal speed than the thumb of the right hand at the slow speed. In all other cases the working speeds differ clearly from each other in magnitude of the motor-cycle intervals.

2. The smallest differences in length of the motor cycles of different fingers are observed at the fast pressing speed, amounting to 50 msec; the optimal and slow pressing rates yield fluctuations of 185 msec between individual fingers.

3. In estimating the distribution of working speed over hands and fingers it can be seen that at the fast pressing speed the left hand does not differ from the right one, but the little fingers lag the others. At the optimal and slow pressing speeds the left hand lags the right somewhat, but the little fingers do not stand out from the rest.

4. Fluctuations in pressing time differ from fluctuations in duration of the motor cycles, but not so sharply as in the case of the first test subject. At the fast pressing speed the magnitude of these fluctuations is approximately equal to the magnitude of the fluctuations of the entire cycle, and at the optimal and slow pressing speeds they are 1/2 the magnitude of the fluctuations of the entire cycle.

Given in Table 3 are data representative of the work of test subject I. B. Comparison of the data of this table with the values considered above reveals the following:

1. the duration of the motor cycles fluctuates for the various fingers at the same pressing speed. But the values of these parameters do not exceed the limits of the given speed in any case;

2. the least fluctuations in duration of the motor cycles of individual fingers are observed at the fast pressing speed, amounting to 35 msec, while the greatest fluctuations (375 msec) are observed at the slow pressing speed. At the optimal pressing speed the fluctuations in duration of the motor cycles for individual figures are 235 msec;

3. the relative pressing speeds for fingers of the right and left hands are the same at the fast speed. At the optimal speed the left hand lags the right somewhat, just as at the slow pressing speed;

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4. fluctuations in the average key-pressing time for the various fingers differ from fluctuations of the entire cycle at the different working speeds. Thus, at the fast pressing rate, fluctuations in the pressing time are 60 msec, i. e., almost double the fluctuations of the entire cycle; at the optimal pressing speed they are also 60 msec, which amounts to 1/4 the fluctuations of the entire cycle, whereas at the slow speed they reach 220 msec, i. e., 0.6 the fluctuations of the entire cycle.

The data given in Tables 1, 2, 3, in addition to the already presented individual differences, also reveal some signs of similarity in the work of all the test subjects. Common for all three test subjects are the following:

1. a distinct difference between the three working rates, evident in the functioning of each of the 10 fingers;

TABLE 3. Mean Values of the Duration of the Motor Cycle and Its Elements (in msec) for Various Pressing Speeds (Test Subject I. B.)

Finger	Speeds (mean data)											
	Fast				Optimal				Slow			
	No. of mea- surements	Length of cycle	Pressing time	Transfer time	No. of mea- surements	Length of cycle	Pressing time	Transfer time	No. of mea- surements	Length of cycle	Pressing time	Transfer time
Right hand												
1-thumb	124	190	90	100	127	325	115	210	103	710	150	560
2-index	147	195	75	120	114	425	90	340	104	700	110	585
3-middle	150	190	80	110	139	260	105	155	139	845	110	745
4-ring	155	180	115	65	126	425	140	285	105	715	135	580
5-little	119	200	135	65	143	400	125	280	112	835	140	695
Left hand												
1-thumb	117	200	110	90	150	350	130	225	100	745	175	570
2-index	145	195	90	105	130	445	95	355	123	895	120	775
3-middle	129	195	90	110	149	285	80	205	103	955	120	835
4-ring	125	210	115	65	128	445	125	320	70	830	125	705
5-little	103	175	115	60	133	400	150	255	61	1075	330	755

2. the smallest fluctuations in duration of the cycles for the various fingers at the fast working rate are 40-50 msec; /114

3. the absolute values of the duration of the motor cycles for each of the given working speeds are close. They fluctuate for the different test subjects from 180 to 270 msec at the fast working speed (4-5 keys/sec), from 285 to 590 msec at the optimal rate (3.5-1.8) keys/sec and from 575 to 1075 msec at the slow rate (1.8-1 key sec);

These figures characterize the extreme limits of the mean values of the cycles at the given working speed, obtained from at least one test subject and for one finger.

4. the fluctuations of the mean duration of cycles with the various fingers are independent of the fluctuations of a single element of the cycle (the key-pressing operation and the pause).

In analyzing the key-pressing motions it was demonstrated that the motor cycle is a better organized (with respect to time) interval than the components of its elements [1]. The same question arises when evaluating finger motions. An estimate of the independence of the cycle elements is attendant upon the following considerations. If the pressing time and the preparatory time for this action (the pause) were separate independent parameters, the sum of their square deviations would equal the mean square deviation of the entire motion of which they are a part. The appropriate calculations are shown in Table 4. From the table it is evident that the mean square deviations of the entire motion at all working speeds were considerably smaller than the sum of the mean square deviations of the pressing and finger transfer actions. Consequently, the duration of the

TABLE 4. Mean Square Deviations (in msec) of the Time of a Motor Cycle and Sum of the Mean Square Deviations of the Elements Making up the Motion (key-pressing and finger-displacement actions)

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Finger	Test subjects					
	V. G.		E. F.		I. B.	
	σ (motor cycle)	Sum σ of the key-pressing and finger transfer act.	σ (motor cycle)	Sum σ of the key-pressing and finger transfer act.	σ (motor cycle)	Sum σ of the key-pressing and finger transfer act.

Fast speed

Right hand

1-thumb	—	—	11,5	17,5	10,0	14,4
2-index	22,5	44,6	14,4	17,4	10,0	38,9
3-middle	13,2	29,9	12,4	27,3	14,1	25,9
4-ring	16,9	43,4	14,2	37,6	21,0	73,5
5-little	18,5	52,9	14,5	50,0	13,5	49,6

Left hand

1-thumb	—	—	15,3	26,9	13,4	32,4
2-index	22,5	63,4	13,2	16,8	17,6	30,7
3-middle	26,6	57,6	15,8	28,7	20,3	48,3
4-ring	29,5	54,8	15,9	32,6	88,0	93,0
5-little	30,1	73,7	17,8	43,0	44,9	74,2

Optimal speed

Right hand

1-thumb	—	—	25,6	40,2	24,1	54,7
2-index	13,7	23,8	26,3	45,0	23,6	47,2
3-middle	14,0	24,6	18,0	47,6	38,9	55,0
4-ring	31,8	48,0	19,0	34,8	22,5	70,0
5-little	39,1	67,5	36,9	54,7	28,0	42,5

Left hand

1-thumb	39,4	91,7	24,3	40,2	16,3	31,8
2-index	18,5	37,8	26,2	43,9	29,1	75,6
3-middle	23,3	27,4	22,6	50,0	19,8	40,6
4-ring	29,5	58,8	26,9	46,3	28,3	79,8
5-little	33,6	76,2	25,3	49,5	33,2	80,1

Slow speed

Right hand

1-thumb	—	—	38,5	55,2	29,2	53,6
2-index	57,4	141,0	30,9	67,5	102,8	125,0
3-middle	42,9	148,0	57,5	103,0	97,1	105,0
4-ring	48,8	92,8	30,9	55,7	95,3	173,0
5-little	51,2	134,5	38,3	62,0	128,6	144,0

Left hand

1-thumb	—	—	22,1	47,3	29,6	44,0
2-index	53,7	118,0	28,8	62,8	61,5	100,0
3-middle	51,4	136,0	31,1	60,7	47,9	87,0
4-ring	43,8	134,0	40,6	68,0	83,6	107,6
5-little	41,0	159,0	32,2	60,9	195,4	339,0

Note: Commas represent decimal points.

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action and the duration of finger transfer are not independent quantities and we have a right to estimate, as the unit time of motion, the time from the instant the finger is lifted, after completing one pressing action, to the end of the next pressing action, i. e., the duration of the motor cycle.

The time characteristics we obtained for finger motions at the fastest working speed, devoted as the "fast" mode, permit us to state with confidence that there exists a specific mode which is common to all our test subjects. The time characteristics of motion in the fast mode are presented in Table 5.

TABLE 5. Time Characteristics of Finger Motions At the Fast Pressing Rate

Finger	Test Subjects											
	V. G.				E. F.				I. B.			
	No. of measurements	Mean value of cycle (msec)	σ	Coefficient of variation (%)	No. of measurements	Mean value of cycle (msec)	σ	Coefficient of variation (%)	No. of measurements	Mean value of cycle (msec)	σ	Coefficient of variation (%)
Right hand												
1-thumb	—	—	—	—	120	255	11,5	4,5	124	190	10,0	5,2
2-index	113	220	22,5	10,2	138	255	14,4	5,6	147	195	10,0	5,0
3-middle	108	215	13,2	6,2	164	220	12,4	5,6	150	190	14,1	7,5
4-ring	100	230	16,8	7,3	142	230	14,2	6,2	183	155	21,0	11,5
5-little	69	240	18,5	7,7	128	270	14,5	5,4	120	200	13,5	6,8
Left hand												
1-thumb	—	—	—	—	74	265	15,3	5,8	117	200	13,4	6,7
2-index	104	245	22,5	9,2	127	245	13,2	5,4	145	195	17,6	9,0
3-middle	106	255	26,6	10,4	136	235	15,8	6,7	129	195	20,3	10,5
4-ring	101	250	29,5	11,8	134	235	15,9	6,7	125	210	88,1	42,4
5-little	88	250	30,1	12,3	122	260	17,8	6,8	103	175	44,8	25,8

Note: Commas represent decimal points.

The greatest differences between the time of execution of motions by the fingers of one hand did not exceed 50 msec for any of the test subjects. For example, the key-striking time for the middle finger of the right hand of test subject E. F. was, on the average, 220 msec, while the time for the little finger of the same hand was 270 msec. But these differences could even be smaller; for instance, the thumb, index, and middle fingers of the right hand of test subject I. B. were characterized by the same value (190 msec), while the ring and little fingers differed by 20 msec. The times of motion of the fingers of the left hand of test subject V. G. were completely identical.

In two test subjects we observed almost complete agreement in time of motion of the same fingers of the two hands; the differences did not exceed the limits of one σ . In the third test subject these differences reached 2σ in only one case. /117

The fast rates chosen by the different test subjects also were in good agreement with each other. The rates of two test subjects hardly differed and their mean values were 240-250 msec. The third test subject worked somewhat faster, at an average speed of motion of 190 msec. The fastest key-striking speed

reached by our test subjects was 4-5 keys/sec. These values are in complete agreement with the data of Fenn [3], who considers the natural period of the index finger to be 4 cycles per sec, and differ but little from Jackson's results [5], whose test subjects pressed at a speed of 5-6 keys/sec.

The mean key-striking time in our experiment was typical of motions completed in 30-40 sec. In Jackson's experiment the values for the average speed of motion were obtained from the number of strokes made in 10 sec. However, this does not explain the somewhat slower speeds of our test subjects since the pressing speeds remained constant over the entire key-pressing time.

The mean durations of the motions at the fast working rate were characterized not only by the very similar working speeds of the various fingers and test subjects, but also by the relatively small amount of variation characterizing each finger. Very high fluctuations were observed only in the work of the ring and little fingers of the left hand of test subject I. B., who had experience in typing with the thumb, index and middle fingers. The coefficients of variation representative of the work of the other fingers were 5-11%.

The time characteristics of the motions of fingers at the optimal rate are presented in Table 6. This rate was chosen by each test subject as the most comfortable.

In comparing the characteristics of the duration of the motions, it is evident that the difference between the speeds of motion of the various fingers of one hand was 125-160 msec for each test subject. In test subject V. G. it was possible to single out three motions of the fingers of each hand that were almost identical in time, but only two for the other test subjects.

TABLE 6. Time Characteristics of Finger Motions at the Optimal Pressing Rate

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Finger	Test subjects											
	V. G.				E. F.				I. B.			
	No. of measurements	Average length of cycle (msec)	Coefficient of variation (%)	No. of measurements	Average length of cycle (msec)	Coefficient of variation (%)	No. of measurements	Average length of cycle (msec)	Coefficient of variation (%)	No. of measurements	Average length of cycle (msec)	Coefficient of variation (%)
Right hand												
1-thumb	—	—	—	154	405	25,6	6,3	127	325	24,1	7,5	
2-index	123	310	13,7	4,4	91	530	26,3	4,9	114	425	23,6	5,5
3-middle	120	300	14,9	5,0	134	465	18,0	3,8	139	260	38,9	15,0
4-ring	109	380	31,9	8,4	135	475	19,0	4,0	126	425	22,5	5,3
5-little	91	425	39,1	9,2	132	530	38,9	6,9	143	400	28,0	7,0
Left hand												
1-thumb	—	—	—	—	149	450	24,4	5,4	150	350	16,3	4,7
2-index	124	310	18,5	6,0	109	590	26,2	4,5	130	445	29,1	6,5
3-middle	118	325	23,3	7,2	137	480	22,6	4,7	149	285	19,8	7,0
4-ring	105	405	29,5	7,3	134	500	26,9	5,4	127	445	28,3	6,4
5-little	93	495	33,6	7,2	115	535	25,3	4,7	133	400	36,2	9,0

Note: Commas represent decimal points.

The agreement between the rates of motion of the same fingers of both hands was fairly well maintained at this working speed also. The differences between the mean speeds of motion of the same fingers were considerably less than the difference between the fingers of the same hand, and only in one case did they reach 60 msec. In all the pairs we compared there was a slight (15-30 msec) predominance in the working speed of the fingers of the right hand. The average pressing speeds of test subjects V.G. and I.B. were 300-450 msec, and of test subject E.F. this was 450-600 msec.

At this rate the amount of variation in the work of each finger was slight. The coefficients of variation were within the range of 4-9%. Considerable fluctuations were observed only in the work of the middle finger of the right hand of test subject I.B.; the pressing speed of this finger was considerably greater than that of the other fingers in working at this rate. The coefficient of variation of this finger was 15%.

Time characteristics of finger motion at the slow rate. The test subjects were obliged to work at a speed lower by a factor of 1.5 than at the optimal rate. The characteristics of the pressing speeds are given in Table 7. In pressing keys at the fast and optimum rates we observed working characteristics which were common to all the test subjects. The pressing speeds at the slow working rate required a separate description for each test subject.

TABLE 7. Time Characteristics of Finger Motion at the Slow Pressing Rate

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Finger	Test subjects											
	V. G.				E. F.				I. B.			
	No. of mea- surements	Average length of cycle (msec)	σ	Coefficient of variation (%)	No. of mea- surements	Average length of cycle (msec)	σ	Coefficient of variation (%)	No. of mea- surements	Average length of cycle (msec)	σ	Coefficient of variation (%)
Right hand												
1-thumb	—	—	—	—	136	575	38,5	6,7	103	710	29,2	4,1
2-index	100	615	57,4	9,3	124	620	30,9	5,0	104	700	102,8	14,8
3-middle	96	615	42,9	7,0	139	720	57,5	8,2	139	845	97,0	11,5
4-ring	107	610	48,8	8,0	117	645	30,9	4,8	105	715	95,3	13,3
5-little	94	610	51,2	8,4	113	695	38,3	5,5	112	835	128,6	15,4
Left hand												
1-thumb	—	—	—	—	119	625	22,1	3,5	100	744	29,6	4,0
2-index	106	630	53,7	8,5	72	620	28,8	4,6	123	895	61,5	6,9
3-middle	105	610	51,4	8,4	88	760	31,1	4,1	108	955	47,9	5,0
4-ring	102	620	43,8	7,0	115	715	40,6	5,7	70	830	83,6	10,0
5-little	108	595	41,0	6,8	115	735	32,2	4,4	61	1075	195,4	18,2

Note: Commas represent decimal points.

Complete agreement with respect to time of pressing of all fingers was observed in the case of test subject V.G., and, therefore, of course, there was agreement between the characteristics of the same fingers. The speed she chose was 610-620 msec per cycle; in the mean, the ratio of this speed to the speeds of the optimal rate was 1.65:1.

The differences in speed of motion between the fingers of each hand reached 140 msec in the case of test subject E. F. We were able to single out two fingers of each hand which pressed at similar speeds. The pressing speeds of the index fingers agreed completely; there were differences between the remaining identical fingers, approximately equal to one σ . The mean ratios of the values of the slow rate to those of the optimum were 1.35:1 for each test subject.

The differences between pressing speeds for the fingers of the right hand of test subject I. B. were 145 msec, while the differences between the thumb and little finger of the left hand were 330 msec and the duration of the cycles fluctuated in the range 745-1075 msec. There was relative agreement between the thumb characteristics. In the work of the other identical fingers there was no agreement, and the fingers of the left hand worked considerably slower than the same fingers of the right hand.

The amount of variation in the work of each finger was also different for each test subject. The coefficients of variation of test subject V. G. fluctuated in the range 8-10%; those of test subject E. F. were very small, remaining within 3.5-8% at this tempo also. The coefficients of I. B. fluctuated from 4-18%. The mean length of the cycle over the entire run of pressing actions by the index and ring fingers of both hands and by the middle and little fingers of the right hand of test subject I. B. and also of the middle finger of the right hand of E. F. was not constant; rather, we were able to observe two average values of the cycle. During the first 30-70 motions the test subjects worked at a faster speed. For example, the average length of the cycle of motion of the little finger of I. B. was 835 msec with a coefficient of variation of 15.4%. However, the first 60 key-striking actions were executed at a speed of 725 msec with a coefficient of variation of 8.5%, and the next 50 motions at a speed of 945 msec with a coefficient of variation of 7.3%.

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The degree of variability of the work of the various test subjects agreed to some extent with the relative duration of the elements of the motor cycle. Shown in Table 8 are the ratios of the length of the pressing actions to the total length of the cycle at each working rate.

The relations between the length of the pressing action and the length of the entire motion, equal to approximately 0.3-0.4, remained constant for test subject E. F. at all the working rates. Consequently, variations in the working rate of E. F. stem from uniform acceleration or deceleration of both the length of the pressing action and the time of finger displacement. At the same time, this test subject was observed to have the most constant working speeds for each finger and the smallest coefficients of variation.

A distinct reduction in the relative pressing time at the slow speed is observed in the case of test subject I. B., whose coefficients of variation were very high. The average values for the pressing time at the optimal and fast speeds were the same and increased only slightly at the slow rate, whereas the total time of the cycle rose by a factor of 2-3, i. e., the working speeds always changed as a result of a change in the finger-transfer time.

There was a clear decrease in the relative pressing time at the optimal rate in the case of test subject V. G.; it amounted to 0.3 of the length of the cycle,

TABLE 8. Relative Length of the Key-Pressing by the Various Fingers at the Different Working Speeds

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Finger	Test subjects					
	V. G.		E. F.		I. B.	
	right hand	left hand	right hand	left hand	right hand	left hand
Fast speed						
1-thumb	—	—	0,38	0,33	0,47	0,55
2-index	0,55	0,57	0,38	0,39	0,38	0,47
3-middle	0,42	0,53	0,30	0,28	0,42	0,45
4-ring	0,43	0,66	0,29	0,26	0,62	0,55
5-little	0,42	0,72	0,25	0,21	0,64	0,62
Optimal speed						
1-thumb	—	—	0,36	0,31	0,35	0,37
2-index	0,32	0,37	0,38	0,39	0,21	0,21
3-middle	0,32	0,31	0,42	0,33	0,40	0,28
4-ring	0,25	0,32	0,50	0,42	0,33	0,28
5-little	0,26	0,39	0,43	0,37	0,31	0,37
Slow speed						
1-thumb	—	—	0,35	0,27	0,21	0,23
2-index	0,61	0,52	0,30	0,27	0,16	0,14
3-middle	0,41	0,50	0,41	0,23	0,13	0,12
4-ring	0,28	0,49	0,32	0,27	0,19	0,15
5-little	0,28	0,53	0,32	0,29	0,17	0,33

Note: Commas represent decimal points.

whereas at the fast rate this relation was 0.4 to 0.7 and at the slow rate 0.3 to 0.6, i.e., the change in speeds occurred as a result of changes in the speed of finger displacement as well as of a change in the key-striking time.

Obviously, the more stable speed is attendant upon the capability of maintaining constant relations between the elements of the cycle.

The degree of variation in the intervals during which the motor cycles were completed is of interest not only from the standpoints already considered, but also insofar as the aspect of methods of controlling the speed of motion is concerned. In the work of Rokotová [1] it was shown that the uniformity of hand motion (key pressing motion) in solving a specific motor task is based on a central interval-generating mechanism for the execution of the motor cycle. By analyzing histograms of the distribution of motor-cycle intervals good agreement was found with the model proposed by McGill, which describes the operation of a rhythmic mechanism specifying intervals and working under noise conditions. These data were obtained for the case of a complex motor problem and the use of the entire wrist as the effector mechanism. In carrying out the present work, we checked the suggestion that the interval-generating mechanism is most clearly manifest when such a simple motor problem is completed as repeatedly striking the same key and when using such a simple motor act as the participation of one finger of one hand in simple coordination activities.

In order to solve this problem we compiled histograms of the distribution of time intervals during which individual motor acts (motor cycles) were carried

out for all the above-described cases. Presented in Fig. 1 is the distribution of the duration of motor cycles of test subject E. F. for the work of the middle finger of both hands at the three working speeds. /122

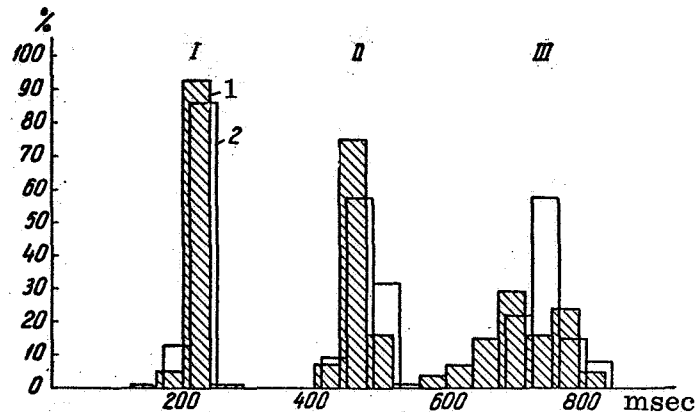


Figure 1. Distribution of the Duration of Motor Cycles for the Middle Finger of Both Hands of Test Subject E. F.:

1, 2—For the Right and Left Hands at the Fast (I), Optimal (II) and Slow (III) Working Speeds.

Deserving of attention is the varying nature of the distribution at the different working speeds of the same fingers and the completely similar nature of the time distribution of finger motion of the hands at the same working speed. The histogram for the fast key-pressing rate consists of one interval in which 85-95% of all cases fall, i. e., almost the entire spread of values for the intervals amounts to 40 msec. Moreover, the value of the peak of the distribution histogram (200-240 msec for the right finger and 210-250 msec for the left) completely describes the time of a motor cycle at the fast pressing speed. The distribution of motor-cycle values at the optimal pressing speed has a somewhat more diffused nature, although it does not change in its essential features (in particular for the right finger). Let us consider the histogram of the right finger. The peak distribution interval (460-500 msec) is very sharply pronounced and takes in 73% of all intervals; the intervals close to the peak one take in 8 and 13% of the intervals and together with the peak interval completely describe the distribution of these values.

The histogram representative of finger operation at the slow speed has essentially a different character. The first thing that strikes our attention is the presence of two peaks for the distribution of cycles of the right finger, which reflects the fact described above, relating to the change in value of the motor cycle at the slow working speed during one and the same execution of this cycle. Furthermore, the histogram reveals the absence of a sharp peak. The values of the intervals are distributed in the range 560-850 msec. Even a rapid survey of the histogram shows that here we are dealing with a process different from the ones governing the fast and optimal speeds. The process is of a more random or, perhaps, inhomogeneous character.

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Let us proceed to evaluate the histograms in connection with evaluating the process on which uniformity of execution of the motor cycles is based. The calculations made by N. A. Rokotova [1] on approximation of the data to the normal distribution and to the distribution of the Laplace function (compound function consisting of regular and random components) led to specific values for the parameters, making it possible to relate the experimental data to one or the other of the distributions. It turned out that the primary parameters were the peak distribution intervals and the intervals closest to them (for the case when the size of the interval is tied in with the value of the mean square deviation and to that of the arithmetic mean).

It was found that the following relative frequencies of occurrence correspond approximately to the normal distribution: 36% for the peak interval, about 24% for the intervals closest to the peak interval; 50-60% of the values in the peak interval will correspond to the Laplace distribution and 15-20% in the adjacent intervals. The peak interval of the optimal speed covers 76% of all values for the right finger and 53% for the left finger. If the histograms are evaluated on the basis of the magnitude of the interval that corresponds to the mean square deviation, the peak of the distribution for the right finger turns out to fall within the interval of 451-470 msec and takes in 53% of all values; the adjacent intervals of 431-450 msec and 471-490 msec cover 18 and 15% of the values, respectively. In the given case, therefore, we are dealing with a distribution of values which are not random, but which reflect the presence of a regular (given) component, in conformity with McGill's model. In order to evaluate the distribution at the fast rate of work let us draw on the values for the relative frequency of occurrence to present the histogram with the magnitude of each interval that corresponds to the mean square deviation (12.5 msec for the right finger and 15 msec for the left). It turns out that 54% of all values is covered by the peak interval, which is, of course, less than the ratios given in the figure, but is considerably closer to the distribution of the Laplace function than to the distribution of the normal (random) function.

Insofar as the distribution of values at the slow speed is concerned, we did not succeed in establishing such clear relations that we could consider the distribution of these intervals as specified.

Thus, from the data we obtained on simple striking of one key by a single finger we can derive information on methods by which the time characteristics of motion are controlled. We believe that these data provide a number of proofs in favor of the viewpoint expressed by Spivack and Levine [8] and others that the time intervals for execution of motions are specified by mechanisms of the human central nervous system. Among these proofs we consider the following:

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1. the great similarity in value of the intervals for all fingers at each given working speed testifies to the possibility that the process is based on a single fixed prescribed interval;
2. the distinct differences between the average values of the intervals at the various working speeds indicates that the working speed is tied in with some interval that is fixed for the given speed;
3. the extraordinary uniformity of the motor-cycle intervals, especially at the fast key-pressing rate;

4. the character of the distribution of the fast and optimal pressing rates, as represented in the histograms.

The experimentally obtained data testify to the high reliability of the experimental approach we used and may serve as a basis for evolving a test which will evaluate the work efficiency of a human operator.

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